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THE IMPACT OF GAS STRIPPING AND STELLAR MASS LOSS ON SATELLITE GALAXY EVOLUTION

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ABSTRACT

Current semi-analytic models (SAMs) of galaxy formation over-predict the fraction of passive small late-type satellite galaxies in dense environments by a factor of two to three. We hypothesize that this is due to inaccurate prescriptions on cold gas evolution. In the hope of solving this problem we apply detailed prescriptions on the evolution of diffuse hot gases in satellites and on stellar mass loss, both of which are critical to model cold gas evolution. We replace the conventional shock-heating motivated instant stripping with a realistic gradual prescription based on ram pressure and tidal stripping. We also carefully consider stellar mass loss in our model. When both mechanisms are included, the fraction of passive late types matches the data much more closely. The satellite over-quenching problem is still present in small galaxies in massive haloes, however. In terms of the detectable residual star formation rates, gradual diffuse gas stripping appears to be much more important than stellar mass loss in our model. The implications of these results and other possibilities, such as redshift-dependent merging geometry and tidal disruption, are also discussed.

1. INTRODUCTION

In the LCDM model, dark matter structures grow via merging and accretion. Within these dark matter halos, baryons initially agglomerate onto the centre of the potential well within the free-fall time of the halo and form stars (Rees & Ostriker 1977; Binney 1977; Silk 1977). When the halo becomes large enough, the accreted gas can be gravitationally shock-heated and turn into diffuse hot halo gas. In the meantime, the constant attraction of gravity causes haloes and their galaxies to interact and merge, forming clusters and groups of galaxies. While orbiting within a host halo, satellite galaxies are likely to interact with other galaxies and the hot ambient gas (e.g. Chung et al. 2007; Yagi et al. 2010). The evolution of the cold and hot gas contents is heavily influenced by the details of these interactions, and the exact mechanism is not well understood.

It is known that galaxies in denser environments are optically redder and more quiescent than field galaxies (to cite a few Gisler 1978; Larson, Tinsley, & Caldwell 1980; Dressler 1980). This strongly suggests that the cold gas supply (the source of star formation) is controlled by mechanisms closely associated with the environment. Gunn & Gott (1972) demonstrated that the cold gas of a galaxy can be stripped off due to the ram pressure exerted on it by the intracluster medium as a galaxy moves within a cluster potential (see also Abadi, Moore, & Bower 1999; Quilis, Moore, & Bower 2000; Chung et al. 2007; Tonnesen & Bryan 2009; Yagi et al. 2010). Tidal stripping is another important process that indirectly affects the evolution of cold gas. Satellites trapped by a larger cluster halo are tidally stripped off their dark haloes and hot gas reservoir.

Throughout their orbital motions, satellites lose their interstellar/diffuse halo gas through shock heating, ram pressure and tidal stripping of their dark halo. Consequently, star formation in satellites may decreases with time. Semi-analytic models (SAMs) of galaxy formation assume that the shock heating is very efficient, and it is generally assumed to *instantly* remove diffuse halo gas from satellite haloes (e.g. Kauffmann et al. 1999). Since the hot gas reservoir is removed instantly, gas cooling stops, cold gas is quickly depleted through star formation and SN feedback, and eventually star formation is quenched. Such models predict that the bulk of satellite galaxies in large haloes should be virtually passive, with only about 20% predicted to be active (e.g. Kimm et al. 2009, hereafter K09).

However, this prediction is not supported by observation. Studies based on the *specific star formation rates* measured from *GALEX* and *SDSS* observations (Salim et al. 2007) have found that a much larger fraction of satellite galaxies are active (Kimm et al. 2009). This is sometimes referred to as the *satellite over-quenching problem* (e.g. Weinmann et al. 2006; Baldry et al. 2006; van den Bosch 2008; Gilbank & Balogh 2008; Fontanot et al. 2009; Kimm et al. 2009).

The assumption of instantaneous shock heating of satellite gases is thought to be the most likely cause of this mismatch between model and data. Observationally, there is evidence for hot gas around satellite galaxies, as shown by *Chandra* observations of early-type galaxies in nearby clusters (Sun et al. 2007; Jeltema et al. 2007). These observations are bolstered by recent hydrodynamical simulations suggesting that a non-negligible fraction (up to $\sim 40\%$) of diffuse hot gas remains associated with satellite galaxies for several Gyrs after merging with the host halo (Bekki, Couch, & Shioya 2002; Kawata & Mulchaey 2008; McCarthy et al. 2008). Various SAMs have included the effect of ram pressure stripping (Khochfar & Ostriker 2008; Kang & van den Bosch 2008; Font et al. 2008; Guo et al. 2010). In a recent attempt Font et al. (2008) showed that inclusion of ram pressure stripping can help improve the bimodal colour

distribution of satellite galaxies and the dependence of satellite colours on galaxy environment (see also Kang & van den Bosch 2008). However, they did not take into account the decay of the satellite orbits due to dynamical friction, and hence their calculations may slightly overestimate the amount of hot gas retained in the satellite systems. Further, as we will show, the instantaneous recycling approximation for stellar mass loss used in the model may change the recent star formation history of galaxies. Alternatively, Weinmann et al. (2010) propose a simple *gradual* recipe for the stripping of gas and dark matter that reproduces the specific star formation rates as a function of clustocentric radius.

Another factor that can contribute to the interstellar medium is stellar mass loss (e.g. Bregman & Parriott 2009). Stellar masses vary widely and their lifetimes depend strongly on their mass. Thus, the stellar mass loss of a population is not instantaneous but changes gradually with time (though the overall change can be dramatic). Yet, most SAMs (Hatton et al. 2003 is a notable exception) have used a simple approach in which roughly 30% - 40% of newly formed stars *instantaneously* evolve off and are recycled to cold gas (e.g. Somerville et al. 2008). This may be a reasonable approximation for long-timescale star formation, but it may not be adequate for investigating short-timescale phenomena, such as the recent star formation history of satellite galaxies.

In this study, we aim to investigate the effects of the two physical processes mentioned above in the context of SAMs. We first consider the orbital motion of a satellite under the influence of dynamical friction and the associated tidal stripping, both of which have been neglected in the previous studies based on EPS (e.g Lacey & Cole 1993) formalism[1]. We also include a prescription for ram pressure stripping (§2.1). Next, in §2.2, we present further improvements on the earlier implementations of stellar mass loss. We finally describe the impact of these considerations on satellite galaxy evolution in §3 and discuss the implications of this in §4.

2. SEMI-ANALYTIC MODEL

We adopt a semi-analytic approach of galaxy formation to investigate the effect of different physical processes on the recent star formation history of satellite galaxies. The fiducial SAM we are using is described in detail in Khochfar & Burkert (2005); Khochfar & Silk (2006). In what follows we briefly lay out the basic ingredients of the SAM and explain the important modifications to the fiducial model.

We generate dark matter halo merger trees for a cosmological volume of $10^6\mathrm{Mpc}^3$ using a Monte-Carlo method developed by Somerville & Kolatt (1999). Within these halos gas cools and collapses at the centre of each halo, forming a rotationally-supported disc galaxy. Star formation in this disc is modeled assuming a Schmidt-Kennicutt law (Kennicutt 1998). Some massive stars quickly die as supernovae and release their energy, which heats up the cold gas in the disk. Note that our fiducial model does not include recycling of mass loss by stellar evolution. When two haloes merge, the most massive galaxy in the more massive halo is set to be the "central" while the other galaxies become "satellite galaxies". These satellites begin to fall toward the central galaxy due to dynamical friction and eventually merge with the central galaxy. If the mass ratio ($= M_{\rm host}/M_{\rm sat}$) between two galaxies is less than 3.5, we assume that the existing stars in both galaxies and the new stars formed by merger-driven starbursts build up the spheroidal component of the merger remnant. It should be noted that galaxy mergers are the only way to form a bulge in our model (c.f Athanassoula 2008). We use a mass ratio-dependent burst efficiency to determine the number of stars formed during the merger, drawn from hydrodynamic simulations (Cox et al. 2008). As galaxies grow, black holes develop as a result of galaxy mergers (Kauffmann & Haehnelt 2000) and become active in suppressing star formation in their host galaxies (Schawinski et al. 2006). Throughout this paper, we use the following set of cosmological parameters: $\Omega_0 = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_{\rm b}/\Omega_0 = 0.15$, $\sigma_8 = 0.77$, and $h = 0.71$.

2.1. *Dynamical Friction and Gas Stripping*

Earlier implementations of the dynamical friction of satellite haloes were based on the Chandrasekhar (1943) formula with a fixed satellite halo mass (e.g. Kauffmann et al. 1999, see however Taylor & Babul 2004 for models with mass loss). Detailed numerical simulations, however, have found that the Chandrasekhar formula systematically underestimates the merging timescales, especially for large mass ratios ($M_{\rm host}/M_{\rm sat} \gg 1$) (e.g. Boylan-Kolchin, Ma, & Quataert 2008).

To delineate the evolution of satellite systems more precisely during halo mergers, we calculate the two-dimensional orbital motions and tidal mass-loss of the satellite halo. We treat each subhalo as a point-like object orbiting in an isothermal host potential. Satellite galaxies embedded in a subhalo are initially placed at the virial radius of the host halo at the beginning of mergers, orbiting with the circular velocity of the host halo (Benson 2005; Khochfar & Burkert 2006). Tangential and radial velocities of the infalling haloes are assigned as $(\eta V_c, \sqrt{1-\eta^2}V_c)$, where η is the circularity defined as the ratio of the orbit angular momentum to that of circular orbit with the same energy. We adopt the random circularity following Lacey & Cole (1993). The exerted dynamical friction is computed as (Binney & Tremaine 1998),

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = -\frac{GM_{\rm sat}(t)}{r^2}\ln\Lambda \tag{1}$$

$$\left(\frac{V_c}{v}\right)^2 \left\{\mathrm{erf}\left(\frac{v}{V_c}\right) - \frac{\sqrt{\pi}}{2}\left(\frac{v}{V_c}\right)\exp\left[-\left(\frac{v}{V_c}\right)^2\right]\right\}\vec{e}_v, \tag{2}$$

where Λ is a Coulomb logarithm and we use the value of $(1 + M_{\rm host}/M_{\rm sat})$ following Springel et al. (2001), V_c is the circular velocity of the halo at the virial radius, v is the orbital velocity of the satellite halo, $\vec{e}$ is the unit velocity vector and r is the distance of the satellite from the centre of the host halo. Here the satellite mass $M_{\rm sat}$ explicitly depends on time.

[1] SAMs based on N-body merger trees can follow the tidal stripping of dark matter subhaloes as long as they are robustly identified. Beyond that point, satellites are tracked based on analytic formalism.

To evaluate the satellite mass $M_{\rm sat}$ during its orbit, we calculate the radius within which the motion of a particle is governed by the satellite. We assume that all satellite mass within the sphere of influence ($r_{\rm soi}$) is bound to the satellite, while the matter outside of $r_{\rm soi}$ is stripped. The sphere-of-influence radius ($r_{\rm soi}$) can be written as (Battin 1987)

$$r_{\rm soi} \sim r\left[\left(\frac{M_{\rm sat}(t)}{M_{\rm host}(<r)}\right)^{-0.4}(1+3\cos^2\theta)^{0.1} + 0.4\cos\theta\left(\frac{1+6\cos^2\theta}{1+3\cos^2\theta}\right)\right]^{-1} \quad (3)$$

where r is the separation between the central and satellite galaxies, $M_{\rm sat}(t)$ is the total (baryon+dark matter) mass of the satellite halo, $M_{\rm host}(<r)$ is the total mass of the central halo within r, and θ is the angle between the line connecting the particle to the center of mass of the satellite halo and the line connecting the centers of mass of the satellite and the host haloes. For large mass ratios ($M_{\rm host}/M_{\rm sat} \gg 1$), Eqn. 3 can be reduced to $r_{\rm soi} \sim r[M_{\rm sat}(t)/M_{\rm host}(<r)]^{2/5}$. At each time step ($\delta t$), we assume that a fraction ($\delta t/t_{\rm dyn}$) of dark matter outside $r_{\rm soi}$ is stripped, where $t_{\rm dyn}$ is the dynamical time scale of the satellite halo. We assume that a galaxy merger takes place if the separation between the two haloes becomes smaller than the size of a central galaxy, which is computed from the observational relationship between galaxy mass and size (Shen et al. 2003). We assume the size of a galaxy to be twice the effective radius. By doing so, the merging time scale obtained from our simple analytic model shows good agreement with the numerical study of Boylan-Kolchin, Ma, & Quataert (2008) (within 20% error).

It is interesting to compare our simple model for mass loss with other studies. Our calculation gives a mass loss of approximately 40% for the dark matter component during the first peri-centric passage, which is comparable to what is found in Taylor & Babul (2004). Note that our calculation does not include the effect of tidal heating. We have also compared our mass-loss curves with results obtained through N-body simulations using GADGET-2 (Yi et al. in prep), and have found qualitatively good agreement.

As a satellite orbits in the host potential, the diffuse gas of the satellite will be stripped due to the ram pressure exerted by the intracluster medium (Gunn & Gott 1972). We model the ram pressure following the analytic formulation of McCarthy et al. (2008, see also Font et al. 2008). We first compute a radius $r_{\rm ram}$ beyond which ram pressure is able to strip material

$$\rho_{\rm host}(r)v_{\rm orb}^2(t) = \frac{2GM_{\rm sat}(<r_{\rm ram})\rho_{\rm gas}(r_{\rm ram})}{r_{\rm ram}}, \quad (4)$$

where $\rho_{\rm host}$ is the density of the host halo gas, $v_{\rm orb}$ is the orbiting velocity of a satellite, and $\rho_{\rm gas}$ is the gas density of a satellite halo. Similar to $r_{\rm soi}$, we remove a fraction ($dt/t_{\rm cross}$) of diffuse gas outside $r_{\rm ram}$. However, if $r_{\rm soi}$ is smaller than $r_{\rm ram}$, we take $r_{\rm soi}$ as the stripping radius. Using this analytic approach, we obtain halo gas loss of approximately 60% after the first pericentre passage for $(M_{\rm host}/M_{\rm sat}, v_r/v_c, v_t/v_c) = (25, 0.9, 0.7)$, which is comparable to the results of McCarthy et al. (2008). It is worth mentioning that this gas stripping prescription is similar to Guo et al. (2010), however the two models differ slightly in several manners. For example, they adopt a fixed orbiting velocity for satellite haloes, whereas our model follows the evolution of the orbital motion until the galaxy at the center of the halo merges with the central galaxy.

As the outer part of the satellite diffuse halo gas is stripped during its orbit, we assume that the remaining gas quickly restores an isothermal profile by redistributing the mass inside the stripping radius. Thus, the cooling rate becomes smaller as more diffuse gas is lost. Cold gas replenished by the satellite halo gas can subsequently form stars, and supernova explosions are assumed to blow cold gas out into the satellite diffuse halo. This assumption affects the star formation history of satellite galaxies, and we will discuss the implications in §4.

2.2. *Stellar Mass Loss*

A large fraction of stellar mass is believed to be released in the form of cold gas and becomes available as a source of the next generation stars. Stellar evolution and mass loss strongly depend on stellar mass itself. Low-mass stars evolve with a long characteristic timescale, whereas high-mass stars are short-lived and end with dramatic mass loss processes. This difference gives an important characteristic of stellar mass loss for each stellar population. Since the mass spectrum of the population is continuous, stars evolve off the population either through supernova explosion or a planetary nebula process *continually*.

Conventional SAM models often neglect this fact because tracing stellar masses from the entire stellar subpopulations is a computationally expensive task. Instead, they generally calculate the fraction of ejecta for a given stellar population and apply it to all other populations regardless of age. For example, when the Scalo initial mass function (Scalo 1986) is adopted, a stellar population will return roughly 30 percent of its mass during its evolution. Then, the models assume that 30 percent of newly formed stars quickly evolve off and constitute the galaxy's gas component. This may be a reasonable approximation for studies of the long-timescale star formation history of galaxies, but it is not as applicable to short-timescale histories, which are the main focus of our investigation.

In this study we develop an economic prescription whereby stellar mass loss can be approximated with reasonable accuracy. Since massive young stars evolve off quickly and their remnant fraction in mass is low (i.e., a higher mass loss rate), a large mass-loss rate can be expected for galaxies with young populations. On the other hand, if the mean age of a galaxy is high, low-mass stars dominate the stellar mass loss, thereby lowering it. Therefore, one can anticipate the anti-correlation between the stellar mass-weighted age of a galaxy ($\langle t\rangle_m$) and the specific stellar mass-loss rate ($dm'_{\rm loss} \equiv dm_{\rm loss}/{\rm d}t/m_{\rm gal}$).

In order to obtain a relation between $dm'_{\rm loss}$ and $\langle t\rangle_m$, we first compute the lifetime of stars with a broken-power law (Ferreras & Silk 2000), which is obtained from the

data of Tinsley (1980) and Schaller et al. (1992).

$$\frac{\tau_m}{\mathrm{Gyr}} = \begin{cases} 9.694\,(m/M_\odot)^{-2.762} & m < 10M_\odot \\ 0.095\,(m/M_\odot)^{-0.764} & m > 10M_\odot. \end{cases} \quad (5)$$

At the end of their lifetimes, stars will release most of their mass, leaving small remnants such as white dwarf or black holes. The mass locked up in the remnant is approximated following Ferreras & Silk (2000) as:

$$\frac{w_m}{M_\odot} = \begin{cases} 0.1(m/M_\odot) + 0.45 & m < 10M_\odot \\ 1.5 & 10 \le m < 25M_\odot \\ 0.61(m/M_\odot) - 13.75 & m \ge 25M_\odot. \end{cases} \quad (6)$$

Using this, we compute the stellar mass loss of galaxies with a variety of star formation histories, drawn from the fiducial SAM without our new features. Assuming that newly formed stars at each redshift follow the Scalo initial mass function, the specific stellar mass-loss rate is computed as a function of $\langle t \rangle_m$ following cosmic star formation histories. This $\langle t \rangle_m - dm'_{\mathrm{loss}}$ relation will be used to estimate the approximate amount of stellar mass loss for a given simulation period ($= dm'_{\mathrm{loss}} m_{\mathrm{gal}} \mathrm{d}t$) in our SAM. This approximation is very reliable for ordinary star formation episodes, but it underestimates the mass loss when star formation rates are high (e.g., if there is a merger-driven starburst in the previous time step). In order to compensate for this shortcoming, we explicitly add the mass loss from the youngest stellar population in the model galaxy to the mass loss estimated from the $\langle t \rangle_m - dm'_{\mathrm{loss}}$ relation. This treatment can be expressed as follows:

$$\delta m_{\mathrm{loss}} \simeq [dm'_{\mathrm{loss}}(t_m)\ m_{\mathrm{gal}} + dm'_{\mathrm{loss}}(t_y)\ \delta m_y]\,\delta t \quad (7)$$

where t_m is the mass-weighted mean stellar age of the target galaxy, t_{y} is the mass-weighted mean age of its youngest populations, δt is the integration timestep used in our SAM ($\approx$250 Myr at $z = 0$ and $\approx$80 Myr at $z = 1$), and δm_{y} is the mass of the stars formed since the last time step. Our modeling of non-instantaneous stellar mass loss is simpler than the recent models of Arrigoni et al (2010) or Benson & Bower (2010). They fully consider the mass loss for the past time-steps, and include a metallicity-dependent stellar yield (Portinari, Chiosi, & Bressan 1998; Marigo 2001) in the latter paper, which is neglected in this work.

Fig. 1 shows the specific mass-loss rates of galaxies having a wide variety of star formation histories as grey contours and the $\langle t \rangle_m - dm'_{\mathrm{loss}}$ relation as a solid line. The specific mass-loss rate of a simple stellar population is also shown as a dotted line. Since subpopulations of a galaxy have different ages and younger populations yield more mass loss, the total dm'_{loss} is usually greater than that of a simple stellar population. As expected, the specific stellar mass-loss rate is a strong function of the mass-weighted age of a galaxy. It is interesting to note that stellar mass loss rates are so small that only a population younger than $100 Myr$ can supply enough cold gas to make galaxies switch from passive to active, assuming a star formation efficiency of 2% (Eq. 8).

A major source of uncertainty in our $\langle t \rangle_m - dm'_{\mathrm{loss}}$ approximation is the fraction of stellar mass loss that contributes to the diffuse halo gas and cold disc gas. Parriott & Bregman (2008) show using two dimensional

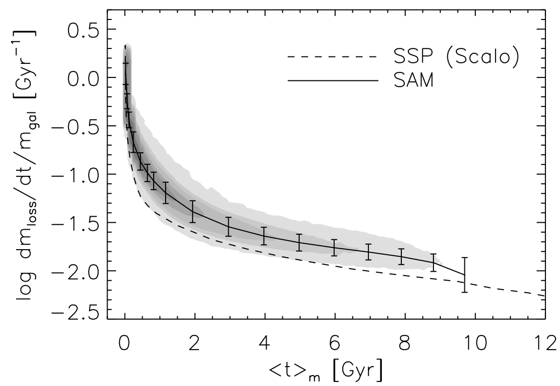

Fig. 1.— The relation between the stellar mass-weighted age of galaxies ($\langle t \rangle_m$) and specific stellar mass-loss rate ($dm'_{\mathrm{loss}} = dm_{\mathrm{loss}}/\mathrm{d}t/m_{\mathrm{gal}}$). Stellar mass-loss is estimated for galaxies with a variety of star formation histories, drawn from a semi-analytic model (gray shading). The mean and 1σ error of this relation is shown as a solid line. The specific stellar mass-loss rate obtained from a simple stellar population with the Scalo IMF is shown as a dashed line. The $\langle t \rangle_m - dm'_{\mathrm{loss}}$ relation is used to approximate the continuous stellar mass loss at each time step.

hydrodynamic simulations including radiative cooling that 25% of the mass loss from red giants remains cool. On the other hand, most of the mass loss from the planetary nebula phase appears to remain warm or cool (Bregman & Parriott 2009). Since the main contribution of the mass loss comes from stars with masses of $2 - 8$ $M_\odot$, whose final stages are planetary nebula, we assume that half of the mass loss goes into the hot halo gas and the rest returns to the cold disc gas reservoir. The exact values of the fractions are unknown, but the models are not very sensitive to such variations (within a factor of two).

2.3. *The effects of the new prescriptions*

In Fig. 2 we show the impact of the two different physical prescriptions on the cold gas evolution for a $2 \times 10^{10} M_\odot$ disc-dominated satellite galaxy. The satellite galaxy can retain a copious amount of cold gas from diffuse gas cooling if it maintains a hot gas halo for an extended period of time. This leads to a further growth in stellar mass in the satellite galaxy. It should be noted that the contribution from stellar mass loss is an order of magnitude smaller than the prolonged gas cooling in this specific example, and results in an order of magnitude increase in cold gas at $z = 0$, compared with our fiducial model where no recycling is used.

3. RESULTS

In this section, we investigate the effect of the two aforementioned physical processes on the recent star formation history of satellite galaxies. There are various ways to quantify recent star formation activity; we make use of the specific star formation rate (SSFR$\equiv$SFR/m_{gal}), obtained from UV and optical photometry. UV lights are much more sensitive to current and recent star formation than optical colours, and, compared with emission line diagnostics, they detect not only on-going but also recent (up to about one billion years) star formation. Empirical specific star formation rates are the values averaged over the past 100 Myr

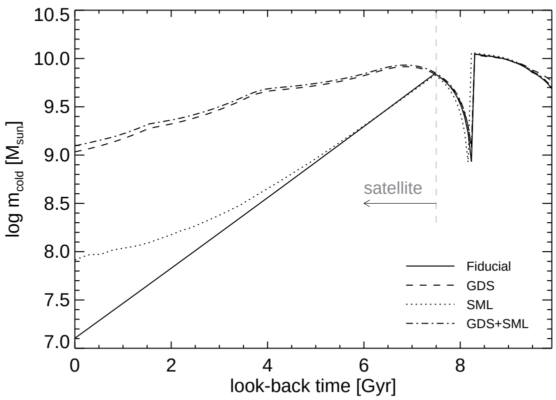

FIG. 2.— The impact of the different physical prescriptions on the cold gas evolution in a sample satellite galaxy. The vertical dashed line marks the moment where a central galaxy becomes a satellite galaxy through a halo merger. The fiducial model (solid line) assumes that the hot gas halo of the satellite is shock heated and instantly stripped away at the time of the merger. Note that the fiducial model does not take into account stellar mass loss. The dotted line shows the model in which stellar mass loss contributes to the cold gas disc. The dashed line shows the model that includes the gradual diffuse gas stripping prescription but not the stellar mass loss. The dash-dot line shows our new model, which includes both features. The rapid drop in cold gas around 8 Gyr is due to a major merger that turned much of the cold gas into stars.

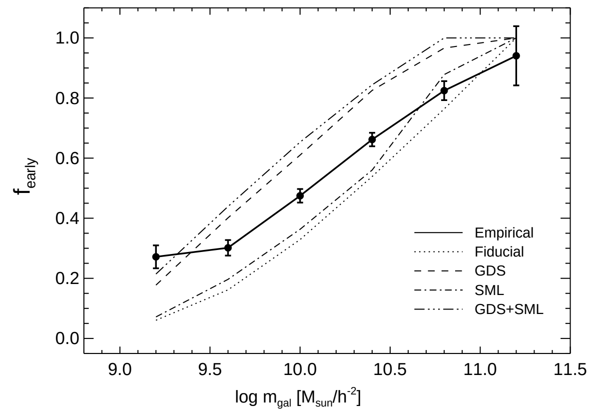

FIG. 3.— The fraction of early-type galaxies ($f_{\rm early}$) as a function of galaxy stellar mass. We assume that early-type galaxies have r-band concentration indices greater than 2.6 in the observational sample.

(Salim et al. 2007) and model values are averaged over the past 270 Myr.

We consider a galaxy "passive" if the following condition is met:

$$\log {\rm SSFR} \leq -9 - 0.2 \log(m_{\rm gal}/h^{-2}M_{\odot}), \qquad (8)$$

We choose this threshold because GALEX ultraviolet detections and star formation rate measurements are robust above this level. This criterion reasonably divides galaxies into active and passive galaxies (see K09).

The observational sample used here is the same used in K09, which is drawn from the GALEX-SDSS matched sample constructed by Salim et al. (2007). K09 also make use of the Group catalog (Yang et al. 2007) for estimates of the dark matter halo mass and galaxy stellar mass. For a more detailed description of the data, readers are referred to K09.

3.1. *Recent Star Formation And Morphology*

Kimm et al. (2009) inspected star formation rates with respect to galaxy mass and halo mass, but did not consider galaxy morphology. It is important to check whether the satellite over-quenching problem is present in all morphological types of galaxies. In order to examine this, we divide the observational data into early and late types using the concentration index in the r-band by requiring that early types have $C_r = r_{90}/r_{50} > 2.6$ (Strateva et al. 2001; Shimasaku et al. 2001). Model galaxies are classified based on stellar mass-weighted bulge-to-total (B/T) ratio. We assume that early types have a B/T ratio of greater than 0.4 (Fig. 3), which is motivated by observational studies (e.g. Simien & de Vaucouleurs 1986), where the division occurs around B/T=0.4.

Fig. 4 shows the fraction of passive satellites ($f_{\rm pass}$) for different morphologies. The observational data (Fig. 4-(a)) show a strong mass dependence of the passive galaxy fraction. Interestingly, the mass dependence of $f_{\rm pass}$ virtually disappears when focusing on individual morphological classes (Figs. 4-(b) and (c)), which implies that the overall mass dependence is a result of a combination of scaling relations among galaxy mass, type, and star formation rates (Fig. 4) (e.g. Park et al. 2007).

The morphological mixture as a function of galaxy mass is reasonably reproduced by our fiducial SAM (Fig. 4). The passive galaxy fractions for early types are reasonably reproduced by most models as long as they include AGN feedback (Schawinski et al. 2006; Kimm et al. 2009). All models present here include AGN feedback. However, most late-type model galaxies do not match observations, as they generally predict that at least 80% of late types must be passive (Fig. 4-(c)). As discussed previously, late-type galaxies cannot maintain the observed level of star formation, most likely because of the lack of cold gas.

Fig. 4-(c) shows how our new prescriptions change the model outputs against the observed late-type galaxies. Model galaxies become progressively more active when stellar mass loss and gradual gas stripping are considered. The inclusion of stellar mass loss alone still produces too many small passive spirals. This is because the amount of stellar mass loss released from old stellar populations in small galaxies is too little to fuel star formation. When both gradual diffuse gas stripping and continuous stellar mass loss are adopted, the passive galaxy fraction becomes closer to the data. As an indication of the sensitivity of the observational fraction of passive galaxies to the actual concentration index cut C_r, we choose a cut of $C_r = 2.4$ as an example. This cut is more conservative in the sense that it provides a cleaner late-type sample. We find that the more strict cut results in a lower passive galaxy fraction ($f_{\rm pass} \sim 0.1 - 0.3$), indicating possible contamination from early-type galaxies within the sample selected using the less conservative cut. It should be noted that our models predict a strong dependence of the passive fraction on galaxy mass for late type satellites, which is not observed. This indicates that the evolution of cold gas in late type satellites is not yet correctly captured by the model.

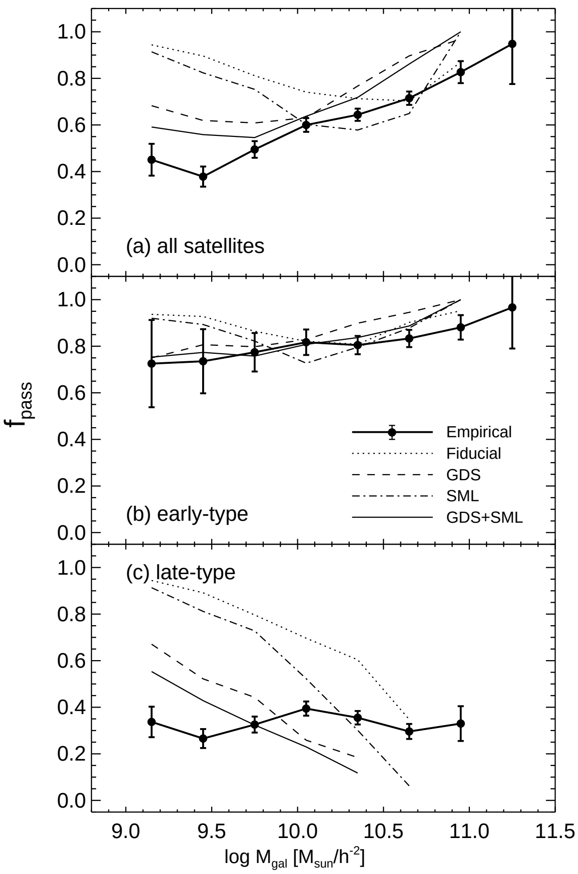

FIG. 4.— The fraction of passive galaxies ($f_{\rm pass}$) as a function of galaxy stellar mass. The top panel shows the $f_{\rm pass}$ for all satellite galaxies. Early-type (middle) and late-type (bottom) galaxies are also shown separately. The empirical data is indicated by solid lines, while our fiducial model (old), the model with gradual diffuse gas stripping (GDS), the model with stellar mass loss (SML), and the model with both GDS and SML are shown by black dotted, green dashed, orange dotted-dashed, and red solid lines, respectively (see chart key). Our original semi-analytic model overproduces passive late types. Note that late-type galaxies become more active (consistent with observations) when GDS and SML are take into account.

The inclusion of stellar mass loss and gradual diffuse gas stripping affects the morphology of model galaxies in a counterintuitive way. Fig. 3 shows that such considerations raise the early-type galaxy fraction. This may sound counterintuitive, because those processes generally enhance the star formation in the disc. However, the morphology (the bulge-to-total ratio) of a satellite galaxy rarely changes due to these considerations. The increase in the disc mass due to prolonged star formation can be large enough to make a galaxy "active", but is too small to change the galaxy morphology. On the contrary, an increase in the stellar disc occurring in the central galaxy leads to increases in the bulge mass of the central galaxy whenever it merges with another galaxy, according to the current semi-analytic prescription. This has the net effect of increasing the number of galaxies with a higher value of bulge-to-total ratio.

Our criterion for passive galaxies is rather conservative, and it is interesting to note that relaxing this criterion to include intermediate colors alleviates the discrepancy between model and observation. This implies our model produces too many intermediate-color late types (see also Weinmann et al. 2010).

3.2. *Environmental Dependence*

The observed fractions of passive satellite galaxies for different environments (halo mass) and morphologies are shown in Fig. 5 (top row). The estimates of dark matter halo masses for observed galaxies are adopted from the Group catalog constructed by Yang et al. (2007). The colour-codings represent different halo masses. As can be seen, both early and late types show an environmental dependence in that star formation activity in larger clusters is suppressed. Again, when the morphology is fixed, the dependence of $f_{\rm pass}$ on galaxy mass and halo mass is weak.

The environmental dependence can also be found in our original (fiducial) SAM (the second row from the top) where the diffuse halo gas of satellites is instantly shock-heated at the beginning of halo mergers. This can be understood by noting that satellite galaxies in more massive halos merge with their host halo earlier and use up their available cold gas without any replenishment. This mechanism is even clearer for late types, because early-type satellites are more strongly influenced by AGN feedback in our models (Schawinski et al. 2006). Note that more than 80% of the small late types in the smallest haloes (black line) are predicted to be passive in this version, which is inconsistent with observation.

Models with gradual gas stripping (third row from the top) shows a better match to the data. The extended cold gas supply preferentially lowers the passive galaxy fraction of massive galaxies. This is because the gravitational restoring force of such systems is usually strong enough to retain a large amount of halo gas. Since the ram pressure becomes less effective if the mass ratios between the host and the satellite halo are comparable, galaxies in less massive haloes are more likely to be active, for a given galaxy mass. However, this model still predicts that a substantial fraction of small late types in massive haloes are passive. Hence, we argue that gradual gas stripping alone cannot reproduce the observed level of recent star formation activity.

The effect of stellar mass loss on recent star formation history appears to be smaller than that of gradual diffuse gas stripping (fourth row from the top). Most galaxies in large haloes are predicted to be passive, which is inconsistent with observation. It seems that stellar mass loss alone cannot maintain the observed level of star formation of late types in cluster environments. This is still true even if we arbitrarily allow 100% of the stellar mass loss to contribute to the cold phase gas. Lastly, the model with both gradual diffuse gas stripping *and* stellar mass loss shows a further improvement in matching the observed fraction of passive small satellites (bottom row). Since cold gas supplies are established through two channels, the overall passive galaxy fraction is diminished. This model slightly underproduces the massive and passive late types. When the total sample is considered (left column), the models appear to reproduce the observed dependence of passive galaxy fraction on galaxy stellar mass. Based on our simple exercise using gradual diffuse gas stripping and stellar mass loss, we conclude that both contribute to the recent star formation history of

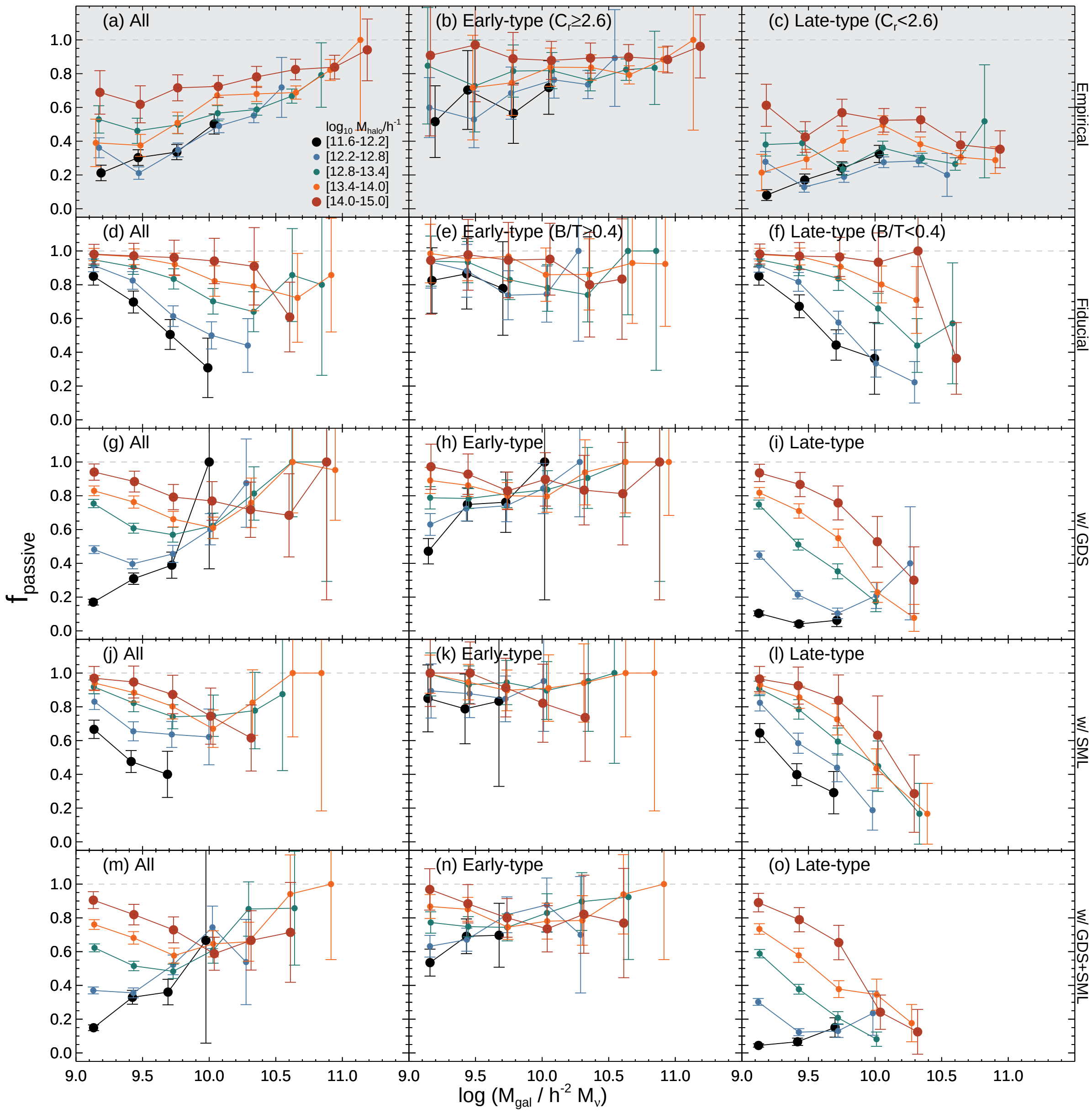

Fig. 5.— The passive fraction of satellite galaxies ($f_{\rm pass}$) as a function of galaxy stellar mass, for different halo mass bins, as indicated by different colours and symbol sizes (see plot legend). Top panels display the observed values. The theoretical models with different prescriptions are shown in the subsequent rows. We present the results for different morphologies, as indicated in the plot. The SAM with gradual diffuse gas stripping (GDS) and stellar mass loss (SML) shows improved agreement with the data, although small galaxies in massive haloes are admittedly still too passive.

satellite galaxies.

4. LIMITATIONS

We have shown that allowing a diffuse gas reservoir and continuous stellar mass loss for satellite galaxies can further supply cold gas, and hence may increase the fraction of actively star-forming spirals in group environments. However, we note that the amount of the supplied gas that is actually used to form stars depends on the mechanism of the supernova feedback.

As an extreme case, if supernovae do not strongly blow out cold gas from discs, more would be available for star formation, and the fraction of passive spirals would decrease. Additionally, satellite galaxies would form stars for a long period of time (e.g Kennicutt 1998) even if diffuse gas reservoir were depleted. On the other hand, if supernova explosion blow most of the cold gas away from the satellite halo, there would be less hot gas remaining. Since the cooling rate is comparable to the blowout rate by supernovae in small subhaloes, where the disagreement in the passive fraction is the most notable, the amount of cold gas would drop rapidly. Then, most of the small galaxies that have already moved around their central galaxy several times are more likely to be passive at $z = 0$ even if they may have their own hot gas halo. This may suggest that satellite over-quenching might not be solely due to inadequate treatment of environmental

effects, but may also relate to how one models supernova explosions.

In this study, we have assumed that supernova explosion cannot blow cold gas away but instead transforms it to hot diffuse gas. Clearly, this is an oversimplification, and further investigation is needed on this subject. It is interesting to note, however, that relaxing the assumption so that the reheated gas can escape the satellite potential would exacerbate the mismatch in the passive fraction for small disc-dominated satellite galaxies. It is also possible that the supernova feedback is ineffective in transforming cold gas into hot gas in the galaxies we discussed (e.g Mac Low & Ferrara 1999; Dubois & Teyssier 2008).

5. CONCLUSIONS AND DISCUSSION

We have investigated the recent star formation history of satellite galaxies by comparing semi-analytic models of galaxy formation with empirical data drawn from SDSS and GALEX. Based on the star formation rate measurements derived from multiband photometry (Salim et al. 2007), we first divided galaxies into active and passive types, and computed the fraction of passive galaxies ($f_{\rm pass}$) as a function of galaxy stellar mass. As already shown in previous studies (Weinmann et al. 2006; Baldry et al. 2006; Kimm et al. 2009), satellite galaxies in theoretical models cannot reproduce the observed level of recent star formation activity. The satellite over-quenching problem is generally attributed to the strong strangulation applied in most semi-analytic models in which diffuse gas of the satellite system is instantly shock-heated from the system at the beginning of halo mergers (e.g. White & Frenk 1991).

In the hope of improving the situation, we implement *gradual diffuse gas stripping* and *stellar mass loss* into our semi-analytic code. For detailed tests, we divide the sample by morphology. We have also introduced an approximation for the contribution to the ISM from stellar mass loss. Our results can be summarised as follows.

- The over-quenched satellite galaxies in SAMs are mostly late-type.
- The models with gradual diffuse gas stripping resolve much of the satellite over-quenching problem. However, they cannot account for the significant fraction of actively star-forming small late-type galaxies observed in massive haloes.
- Stellar mass loss is not a dominant source of cold gas in most satellite galaxies but enhances residual star formation.
- Our new models incorporating both effects show a significantly-improved match to the observed data. However, they still suggest that the majority of cluster late types are passive.

Recent SAMs including ours have shown steady progress in matching the observed data, but are missing key ingredients. For example, feedback from supernova explosions affects the recent star formation history in satellite galaxies by regulating the remaining cold disc gas but is still poorly constrained (§4).

One might wonder whether or not simply increasing the contribution of stellar mass loss to the cold ISM can reproduce the passive late-type fraction. We have found that such an approach still shows a lack of actively star-forming late types. Kaviraj et al. (2007) reached a similar conclusion when trying to explain early-type galaxies with residual star formation (Yi et al. 2005).

Recently, Tonnesen & Bryan (2009) demonstrated that a *weak* ram pressure does not only remove cold gas in satellites but also may enhance star formation by compressing the gas component. Provided that the cooling of cold gas onto a galaxy disc is suppressed during the interaction between the host and satellite haloes and the satellites are affected by the weak ram pressure for a long time, this may increase $f_{\rm pass}$ by consuming a significant fraction of cold gas. Yet, it is still unclear how gas cooling takes place in massive satellite systems during halo merging. Since cooling also relies on the density, if ram pressure compresses both cold and diffuse gas, cooling could also occur more efficiently. If this is the case, the efficient cold gas consumption might have little effect on $f_{\rm pass}$. Detailed numerical simulations are necessary to better understand the supply of cold gas during interactions.

An accurate determination of initial orbits may have an impact on $f_{\rm pass}$. Based on numerical simulations at $z \sim 0$ (Benson 2005; Zentner et al. 2005; Khochfar & Burkert 2006), we have assumed that satellite galaxies have random circularities at the time of halo mergers over the entire cosmic history. If radial orbits are more common at higher redshifts (e.g. Wetzel 2010; Dekel et al. 2009), gas stripping due to ram pressure would be more effective because satellites penetrate dense intra-cluster media more frequently on radial orbits. Motivated by this idea, we performed a simple experiment: we assigned an eccentricity of 1 to the haloes that experience halo merger at $z \geq 1$. In later mergers, orbital parameters were randomly chosen in terms of circularity, as done in the fiducial model. Since massive galaxies are likely to orbit several times while smaller galaxies have passed the pericentre less, the influence of ram pressure on radial orbits is more notable in massive satellite galaxies. As a result, the negative correlation of $f_{\rm pass}$ with $m_{\rm gal}$ shown by our new late-type galaxy models in massive haloes gets diminished, making the models match the data slightly better. However, the reliability of our exercise depends on the validity of the demarcation redshift and actual eccentricity distribution assumed.

We also note that ignorance of the tidal disruption could have an impact on the passive galaxy fraction. Taylor & Babul (2004) and Zentner & Bullock (2003) showed that subhaloes lose 30–40 per cent of their mass per pericentric passage. This implies subhaloes are dissolved into host haloes after several orbits unless they merge with centrals. On this basis, Somerville et al. (2008) implemented a prescription that satellites are disrupted when the subhaloes lose $\sim$ 90% of their initial mass. By doing so, they reproduced the luminosity and the radial distribution of Milky Way satellites (Macciò et al. 2010). Henriques, Bertone & Thomas (2008) also present good matches to galaxy colours using a simple assumption that satellites which are not associated with subhaloes in the Millennium dark matter simulation (Springel et al. 2005) are already disrupted by the tide in their environment. Yet, as discussed in K09, the Somerville et al. (2008) models still show a lack of

actively star forming small satellites, implying that ignorance of tidal disruption is not the primary cause of red and dead small (late-type) satellites. Nevertheless, since it is small red and dead galaxies that are preferentially disrupted by tidal forces, the Somerville et al. (2008) models exhibit a slightly better agreement with empirical data than other semi-analytic models without tidal disruption (see K09 for details). In this regard, the passive galaxy fraction in the low-mass regime could be even smaller, resulting in a weaker dependence of the passive fraction on galaxy mass.

Recent semi-analytic models often adopt AGN feedback to prevent hot gas cooling in massive galaxies (i.e. Croton et al. 2006). The effect has been particularly important for "central" galaxies that are fuelled by ongoing cooling, in contrast to satellite galaxies that cannot retain their hot halo gas in most SAMs. However, the strong strangulation appears problematic in that even late types suffer from the lack of cold gas. For that reason, we demonstrate that external as well as internal gas supply are necessary to match the observed fraction of passive galaxies. Allowing the external supply has an interesting implication. Since the gas retained in the hot halo could funnel into black holes (e.g Croton et al. 2006), AGN feedback is likely triggered, and possibly suppresses star formation activity in satellite galaxies with supermassive black holes. On the other hand, the effect of AGN feedback may be negligible in late-type galaxies because their black holes are not massive enough to release a large amount of energy. Instead, the evolution of late-type galaxies in clusters or groups may be more likely driven by the combination of stellar mass loss and environmental effects such as tidal and/or ram pressure stripping. We have indeed shown to first order that both mechanisms could reproduce observed levels of recent star formation, but it is still unresolved how late-type satellite galaxies show similar fractions of passive galaxies over various galaxy stellar masses for a given halo. Explaining these observations with realistic assumptions is an important challenge, especially since most of the galaxies in the universe are satellites.

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